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Juliano et al.

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(54) **METHODS AND APPARATUS FOR MAGNETRON SPUTTERING**

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(51) **Int. Cl.**
C23C 14/35 (2006.01)

(52) **U.S. Cl.** **204/192.12**; 204/298.18; 204/298.19; 204/298.2

(58) **Field of Classification Search** 204/192.12, 204/298.17, 298.18, 298.19, 298.2
See application file for complete search history.

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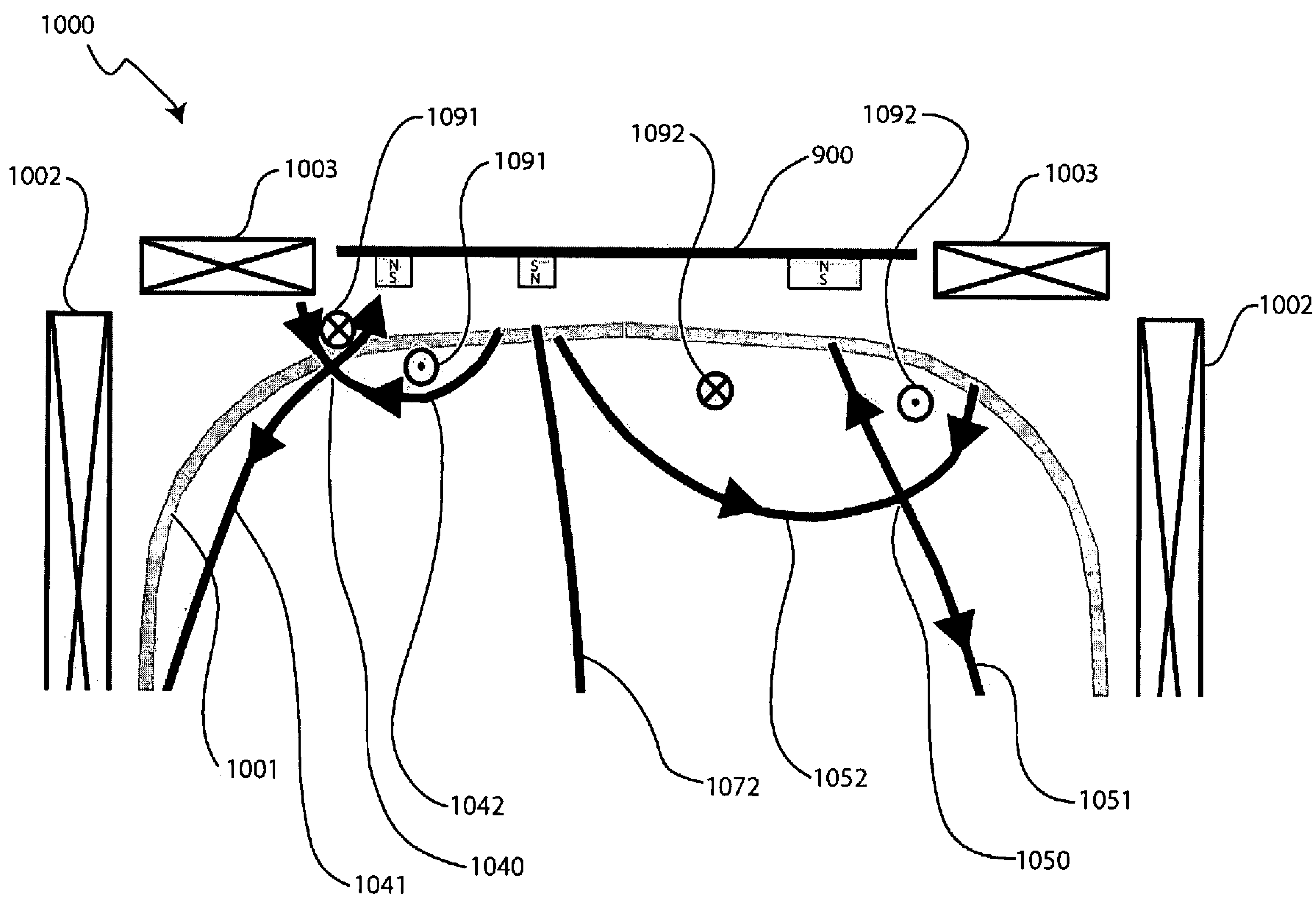
(74) *Attorney, Agent, or Firm*—Okamoto & Benedicto LLP

(57) **ABSTRACT**

In one embodiment, a magnetron sputtering apparatus forms a closed plasma loop and an open plasma loop within the closed plasma loop. The open plasma loop allows for relatively uniform erosion on the face of a target by broadening the sputtered area of the target. The open plasma loop may be formed and swirled using a rotating magnetic array to average the target erosion.

12 Claims, 12 Drawing Sheets



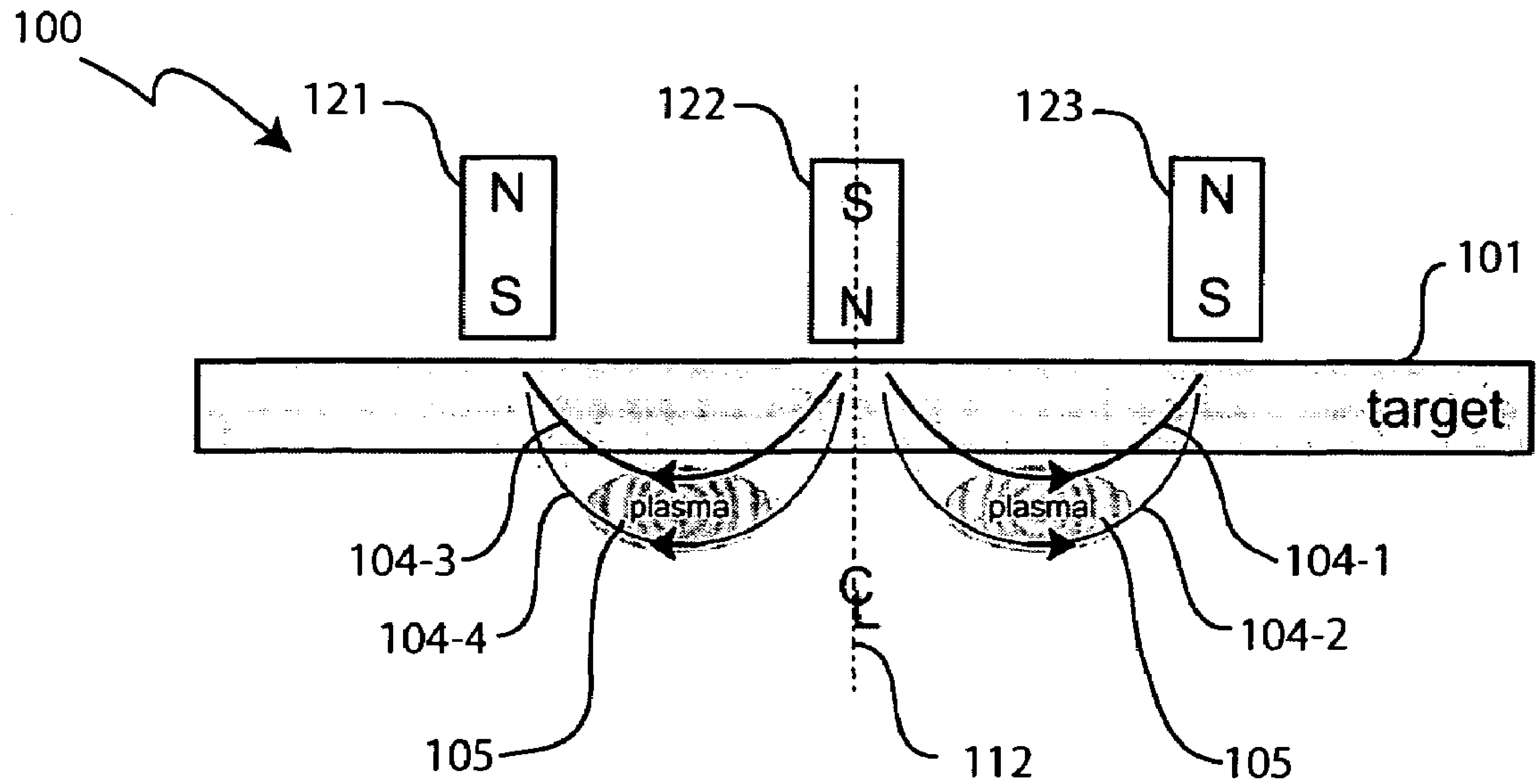


FIG. 1A
(PRIOR ART)

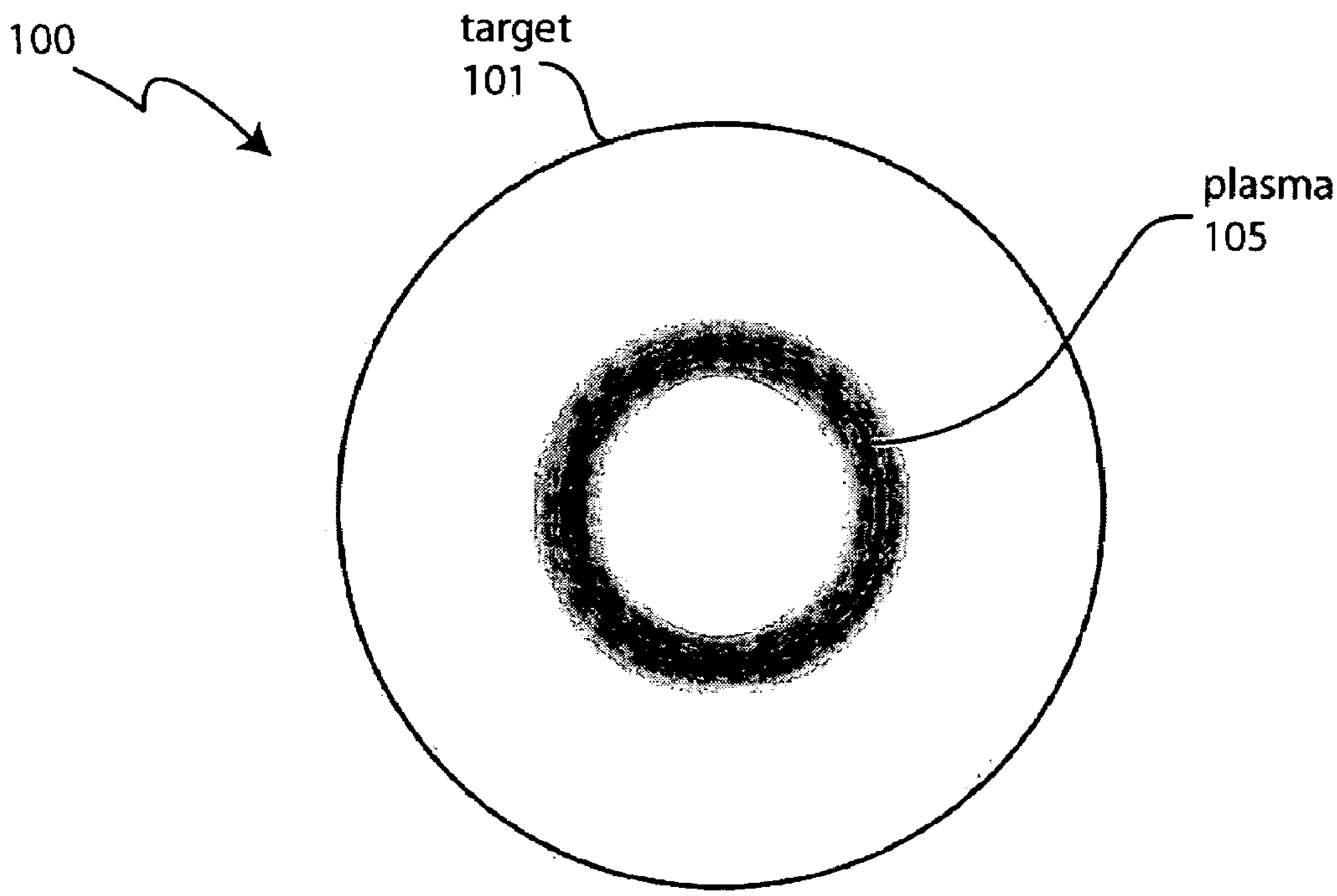


FIG. 1B
(PRIOR ART)

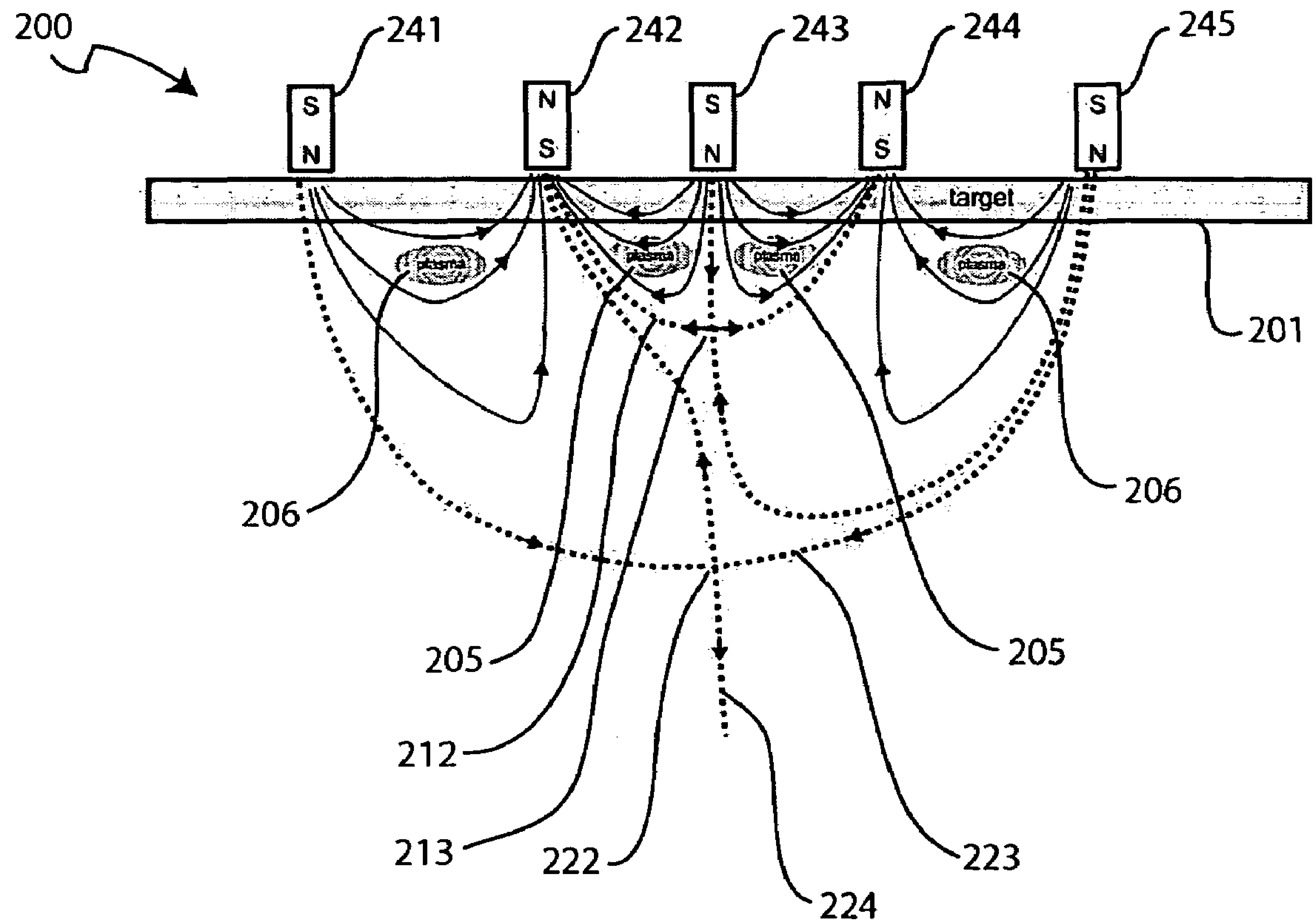

200
241
242
243
244
245
S
N
N
S
S
N
N
S
S
N
target
plasma
plasma
plasma
plasma
201
206
206
205
205
212
213
222
223
224

FIG. 2A

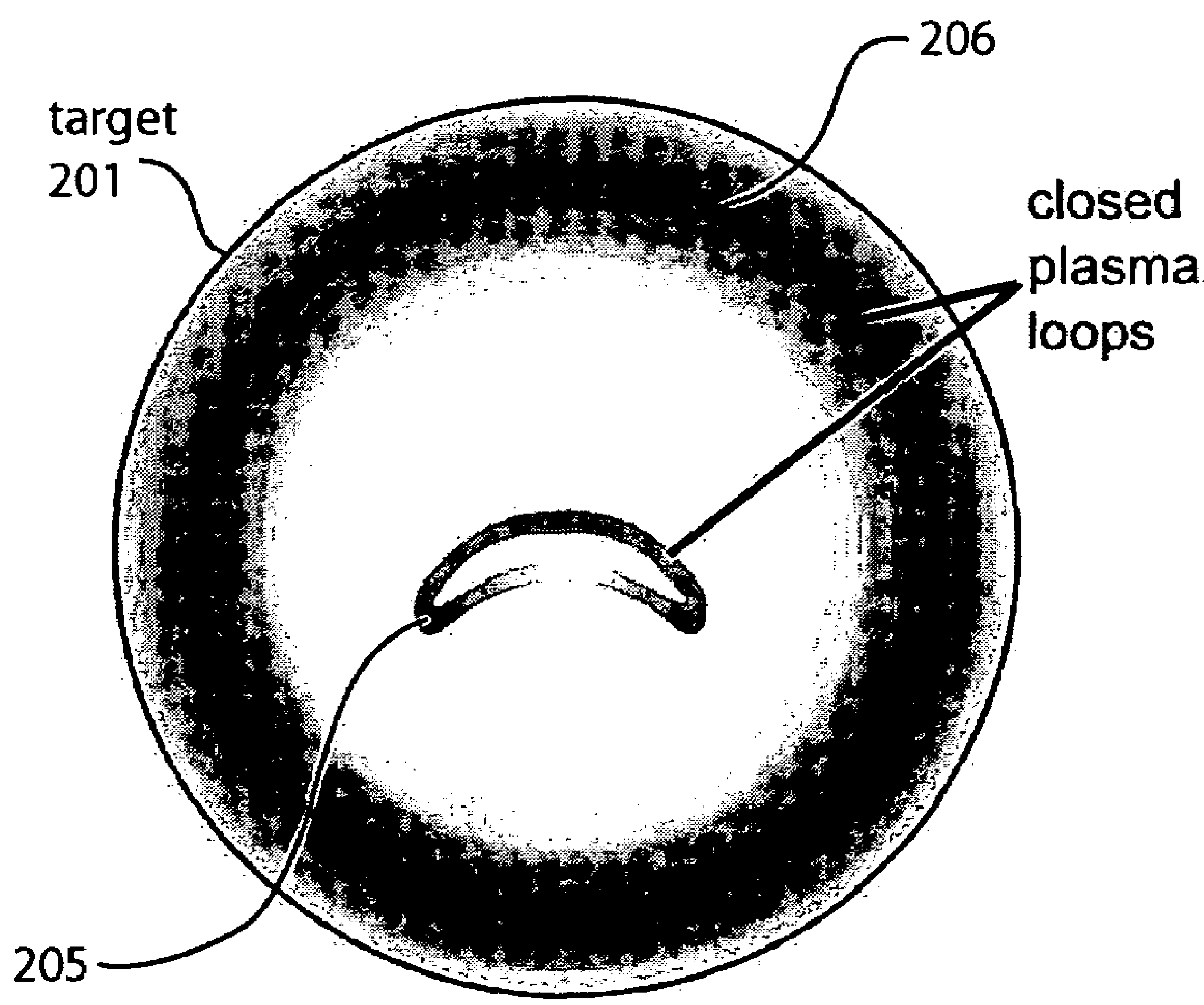

206
target
201
closed
plasma
loops
205

FIG. 2B

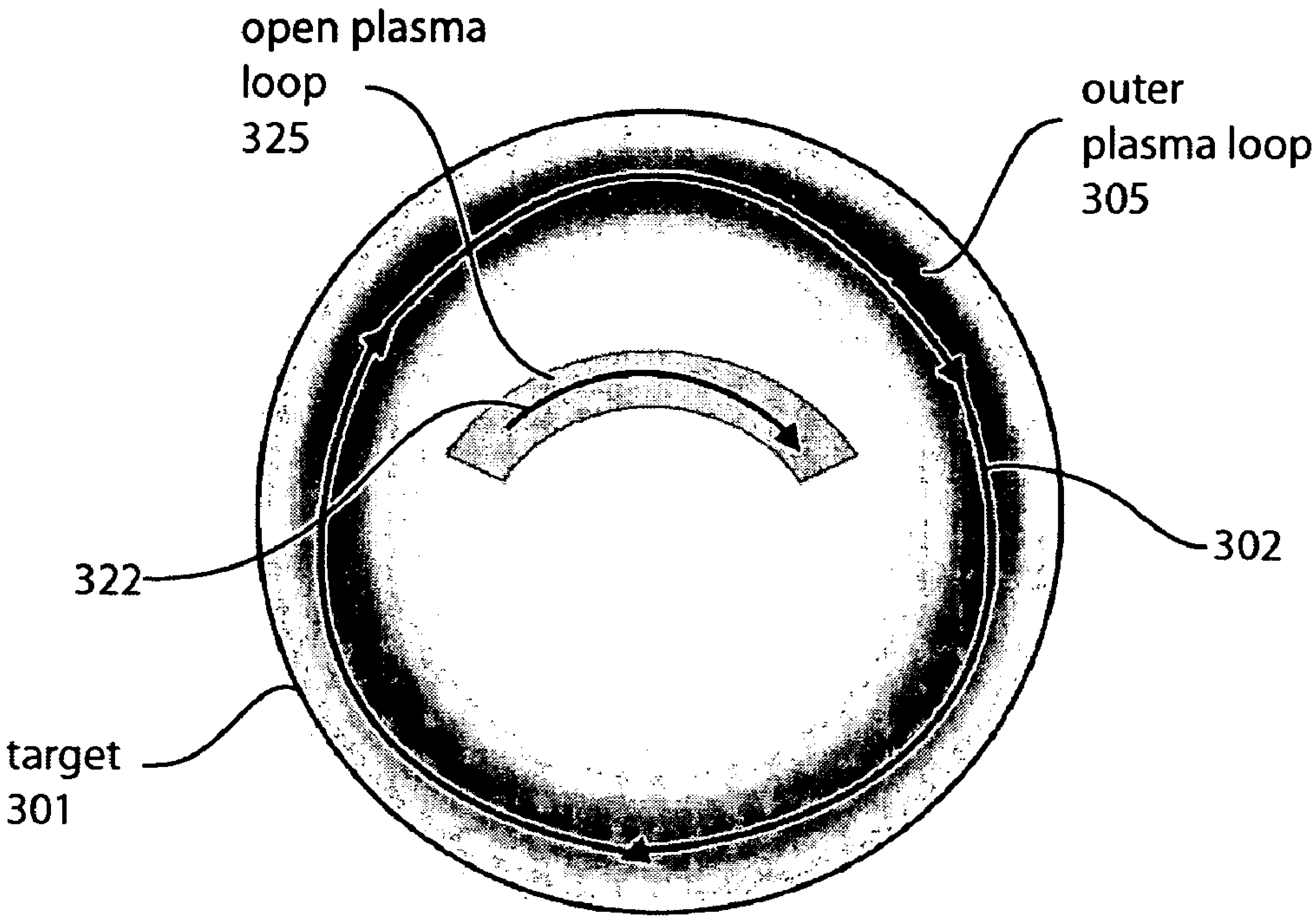

open plasma
loop
325
outer
plasma loop
305
302
322
target
301

FIG. 3

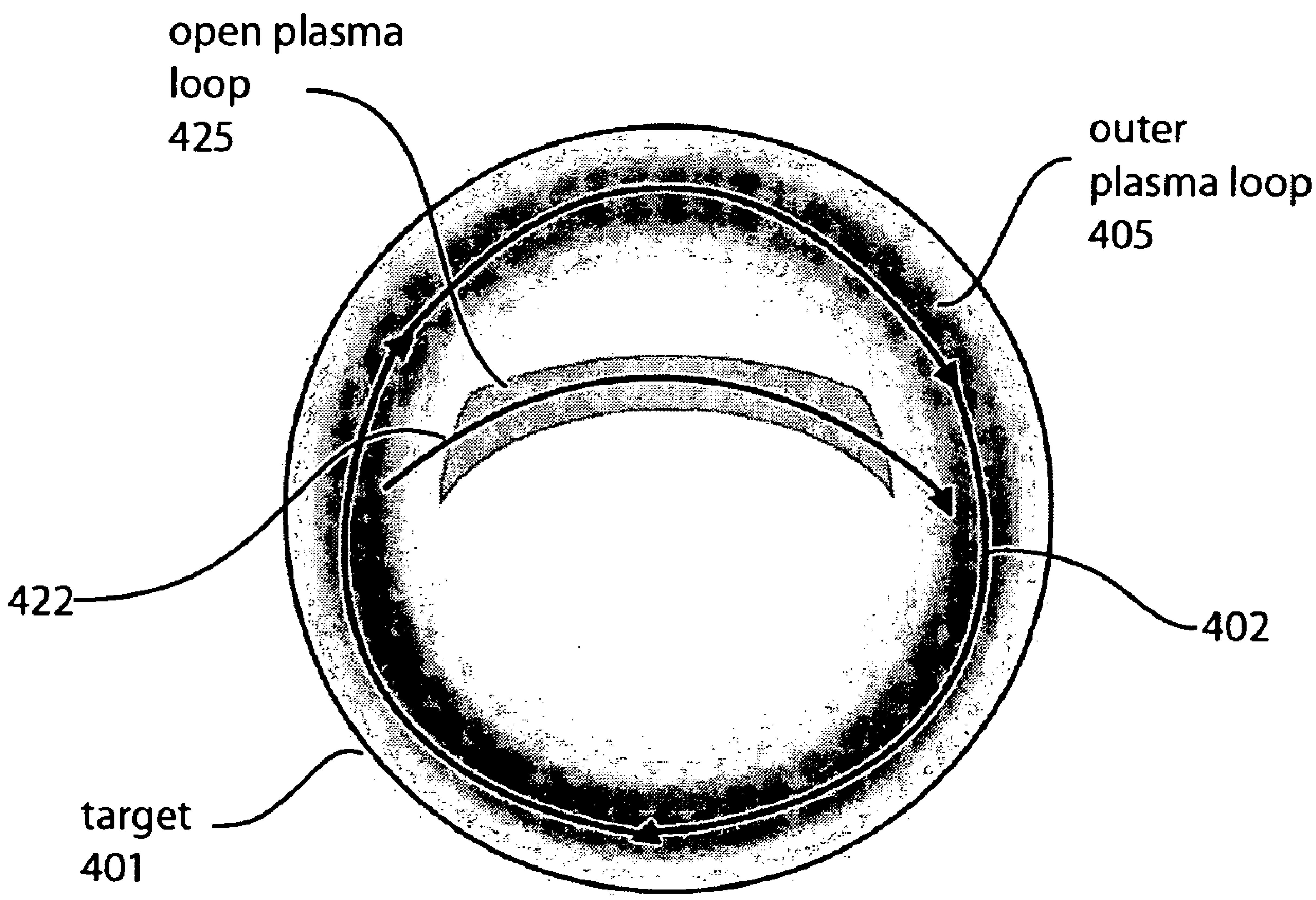

open plasma
loop
425
outer
plasma loop
405
402
422
target
401

FIG. 4

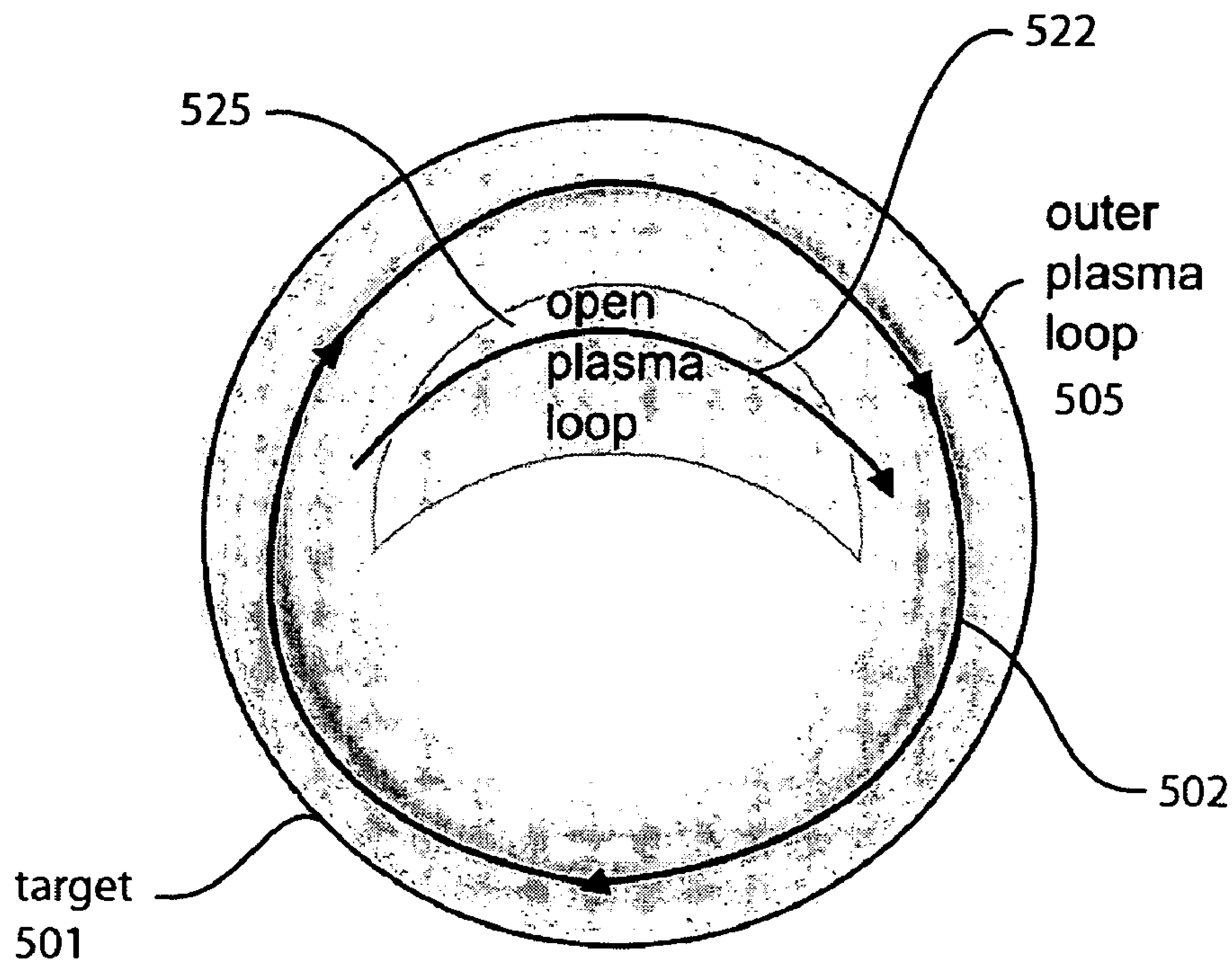

522
525
outer
plasma
loop
505
open
plasma
loop
502
target
501

FIG. 5

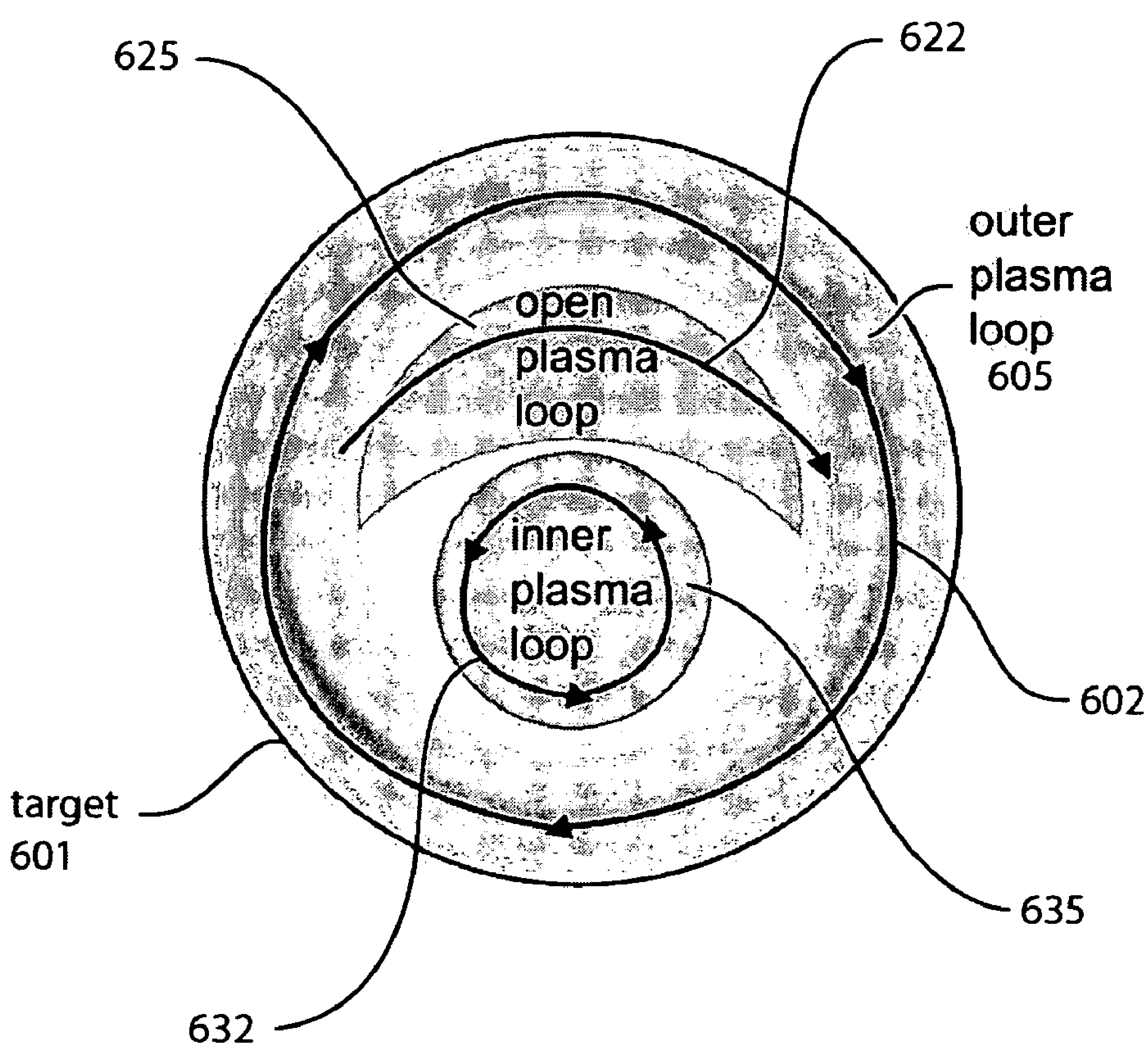

625
622
outer
plasma
loop
605
open
plasma
loop
inner
plasma
loop
602
target
601
635
632

FIG. 6

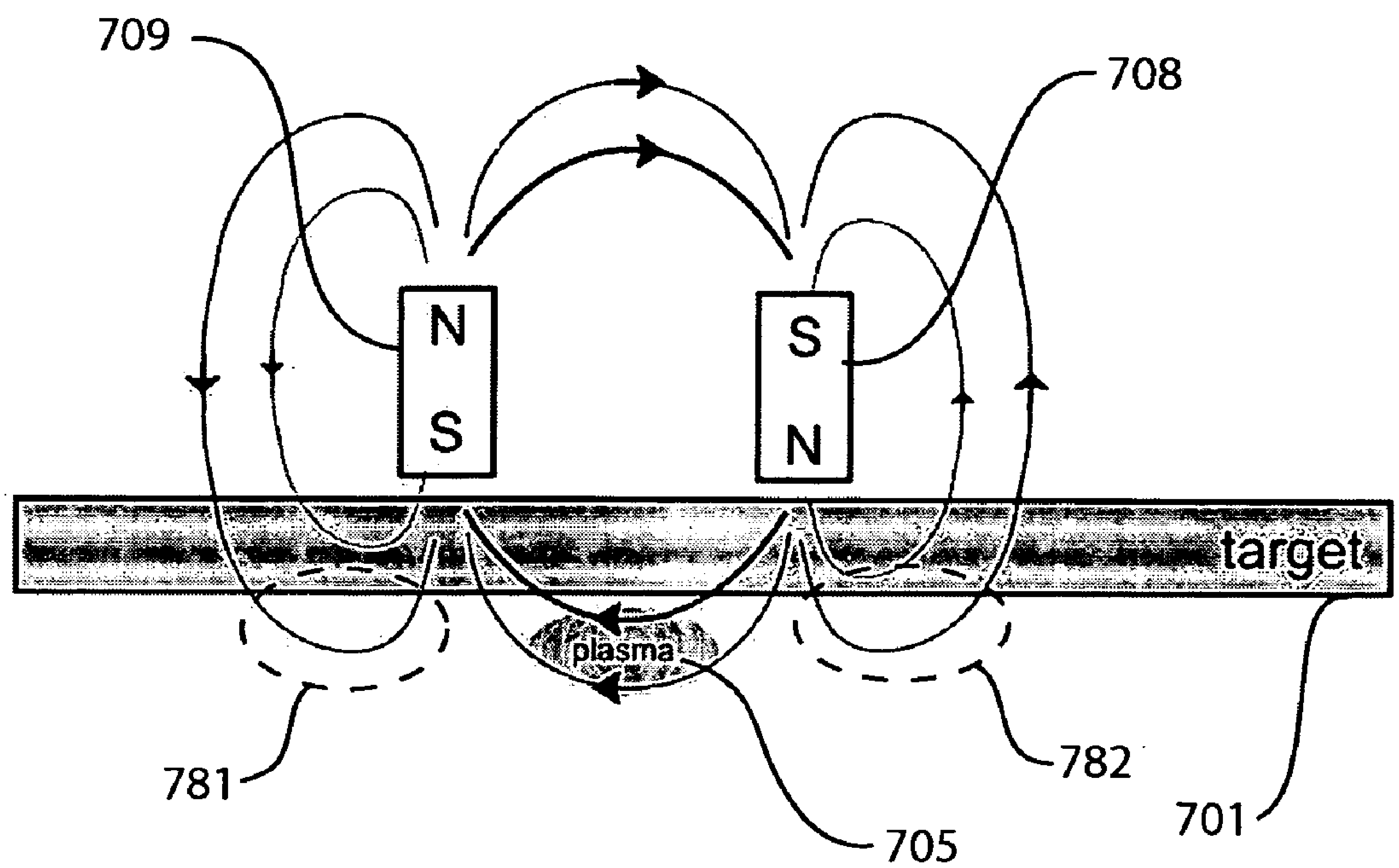


FIG. 7A

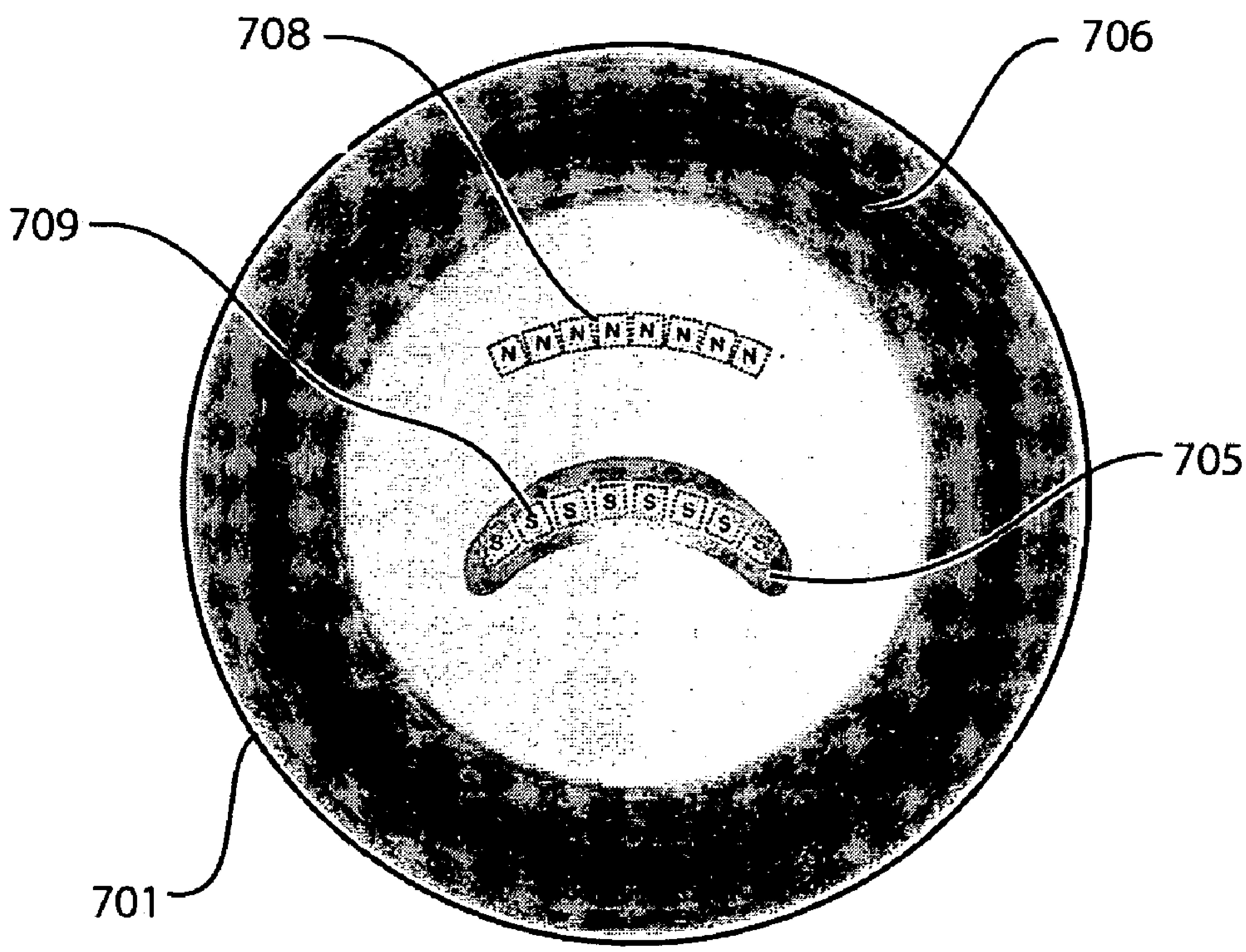


FIG. 7B

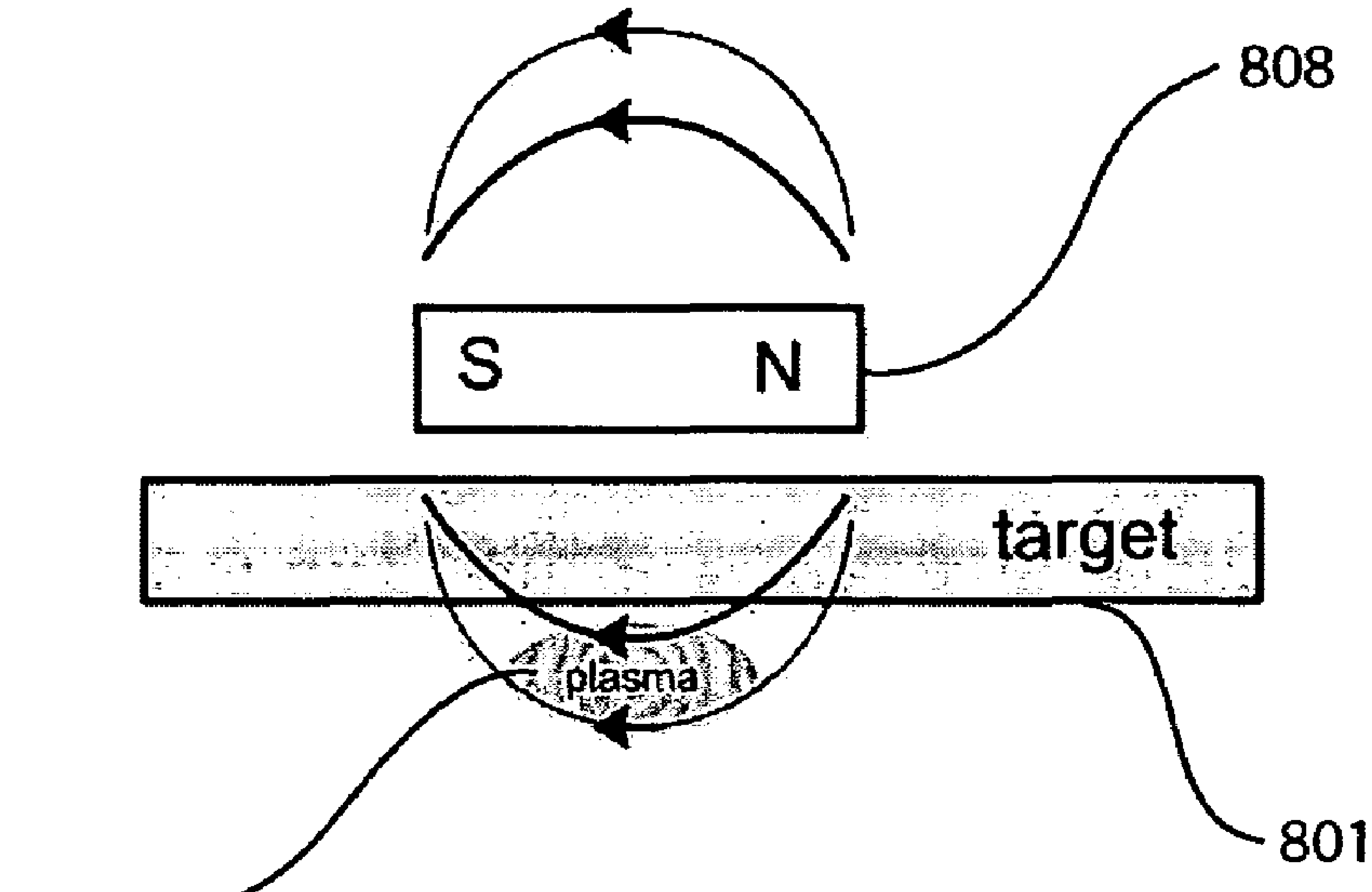


FIG. 8A

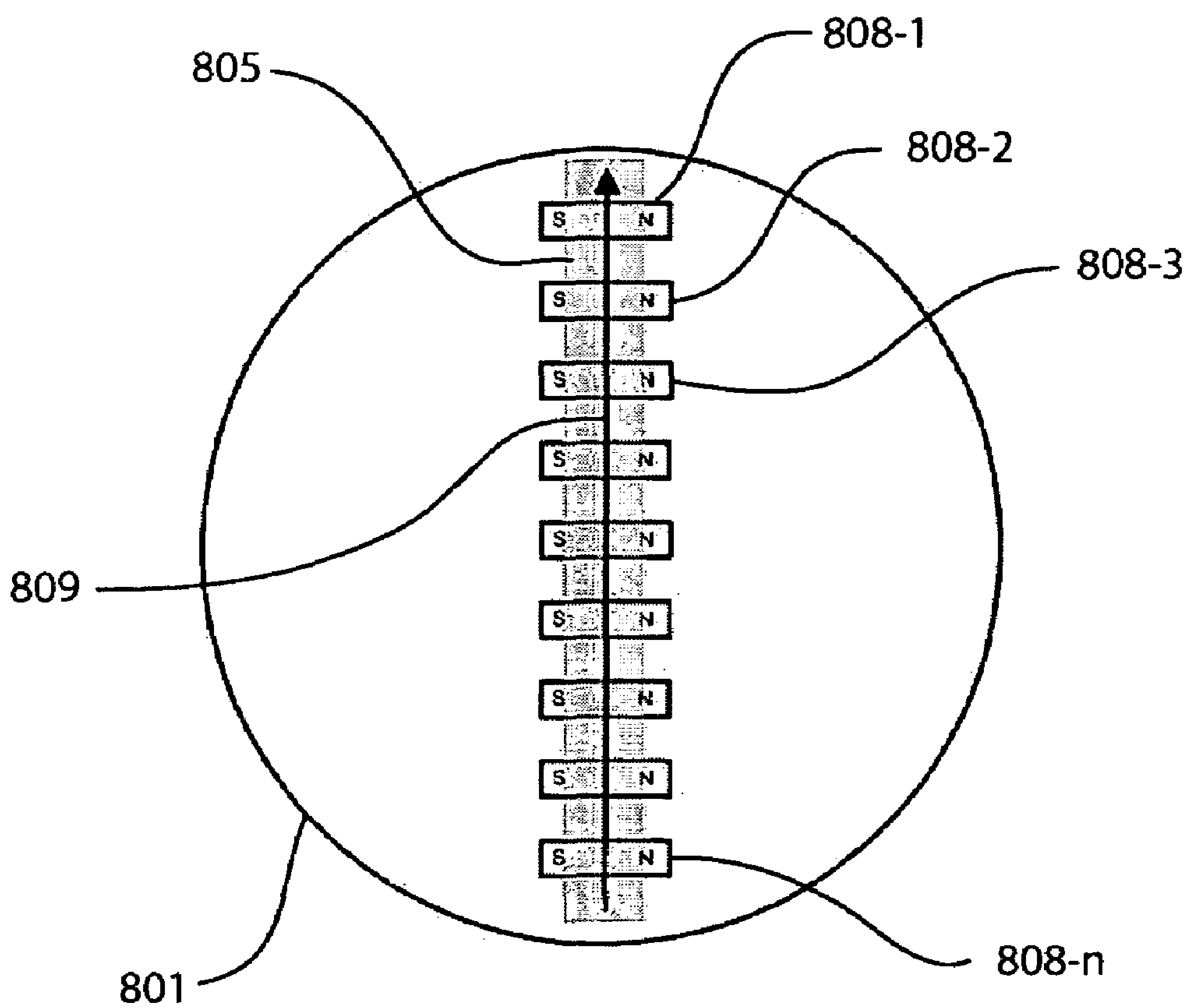


FIG. 8B

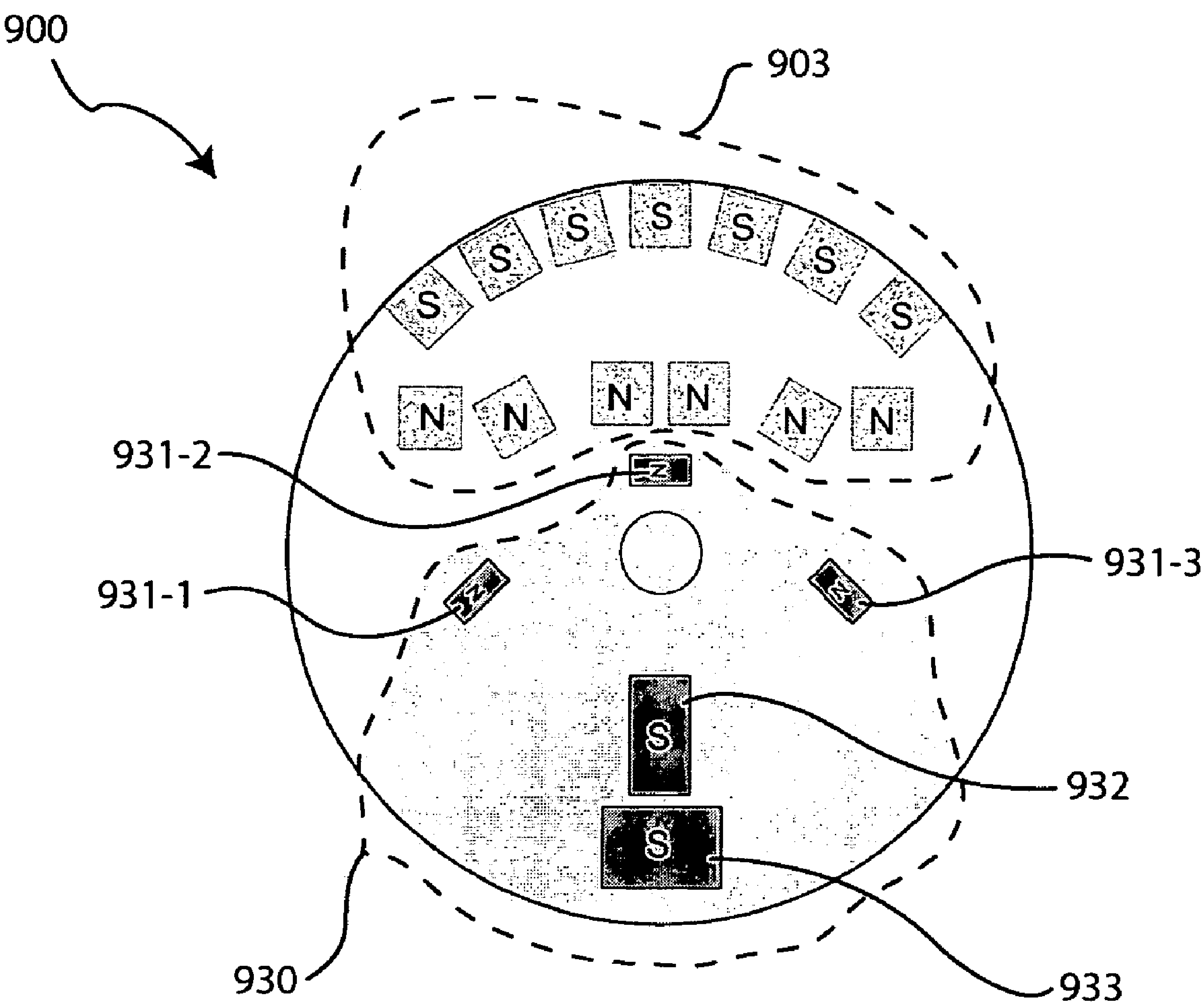


FIG. 9A

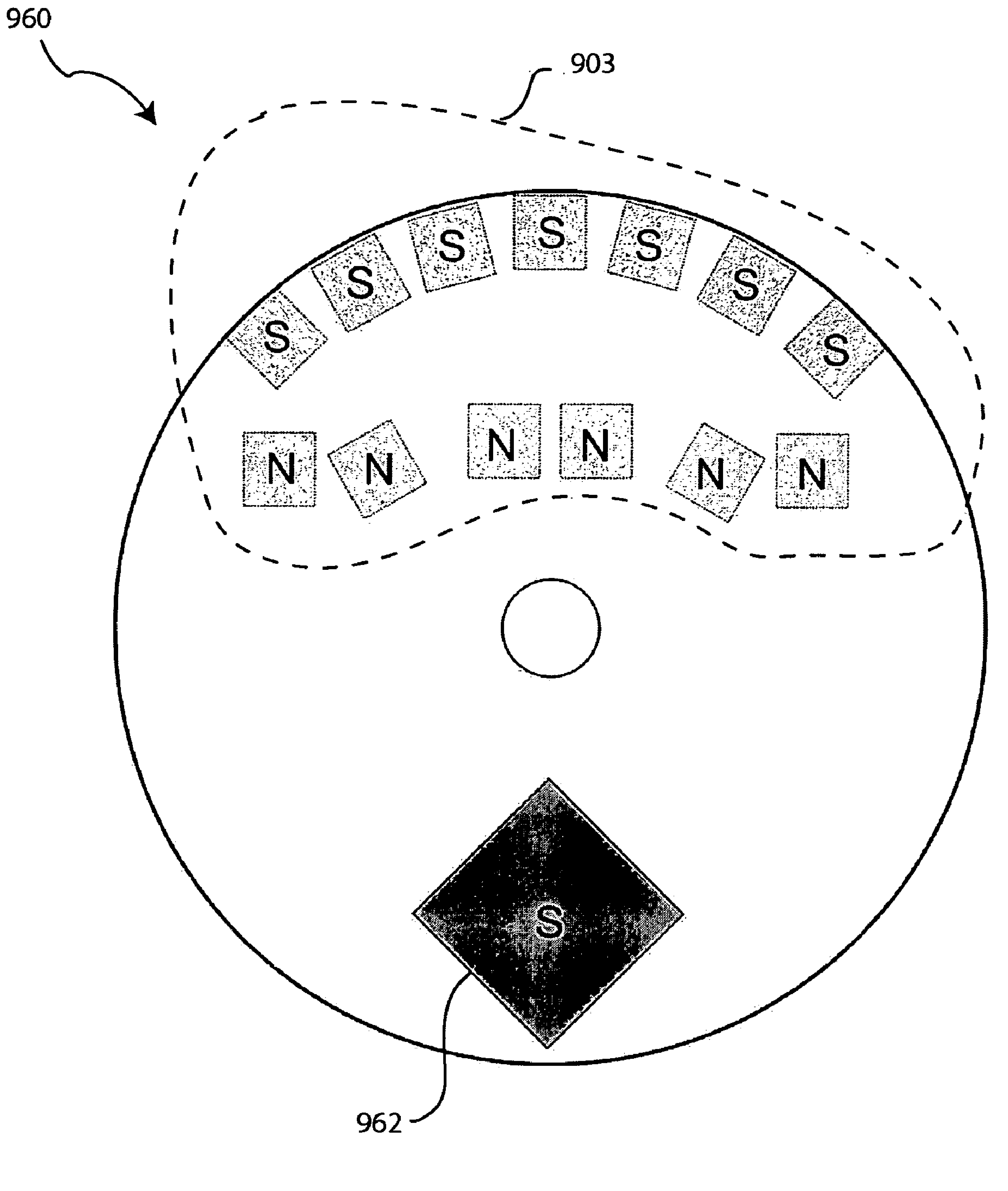


FIG. 9B

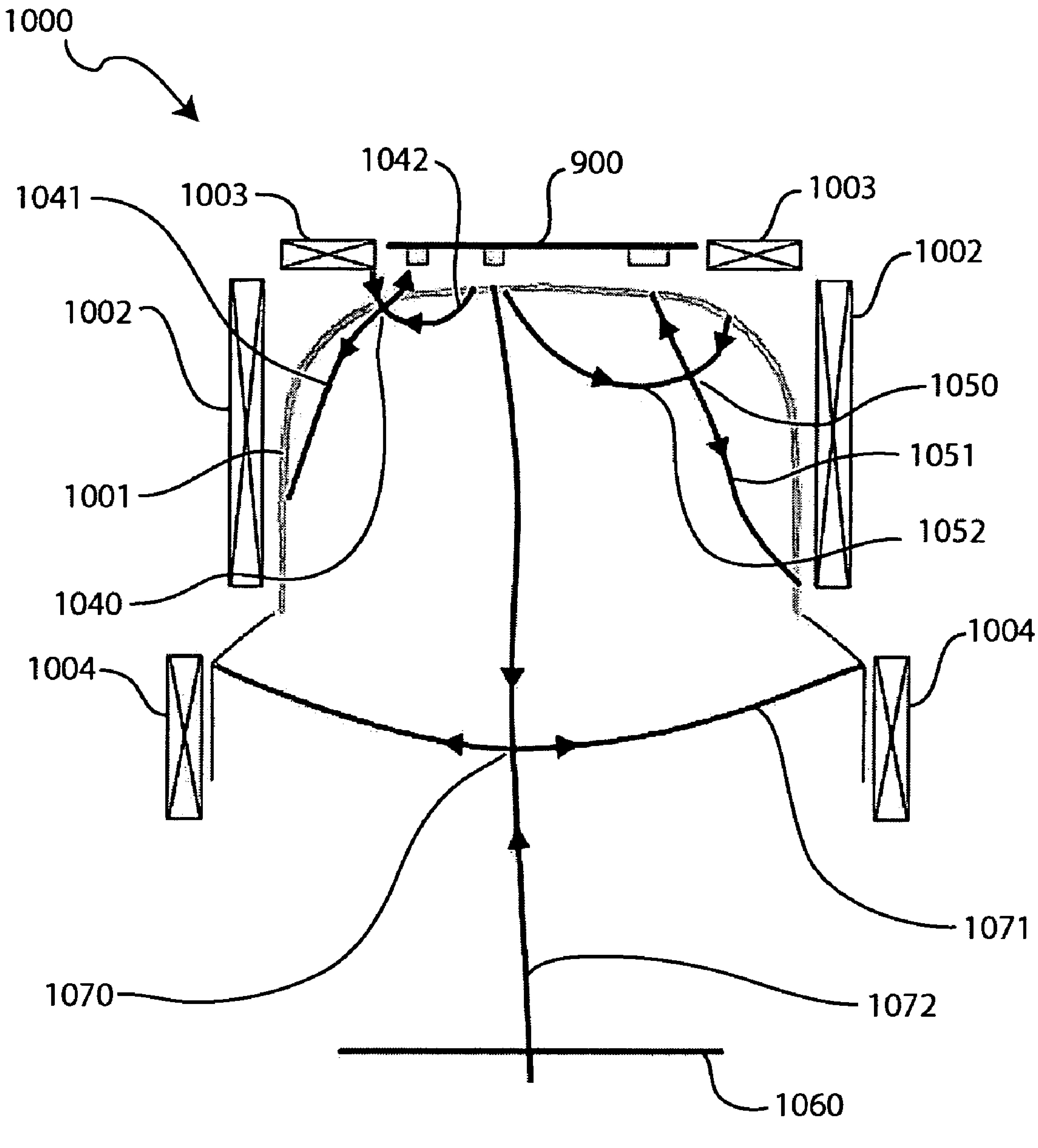

1000
1042
900
1041
1003
1003
1002
1002
1050
1051
1001
1052
1040
1004
1004
1071
1070
1072
1060

FIG. 10A

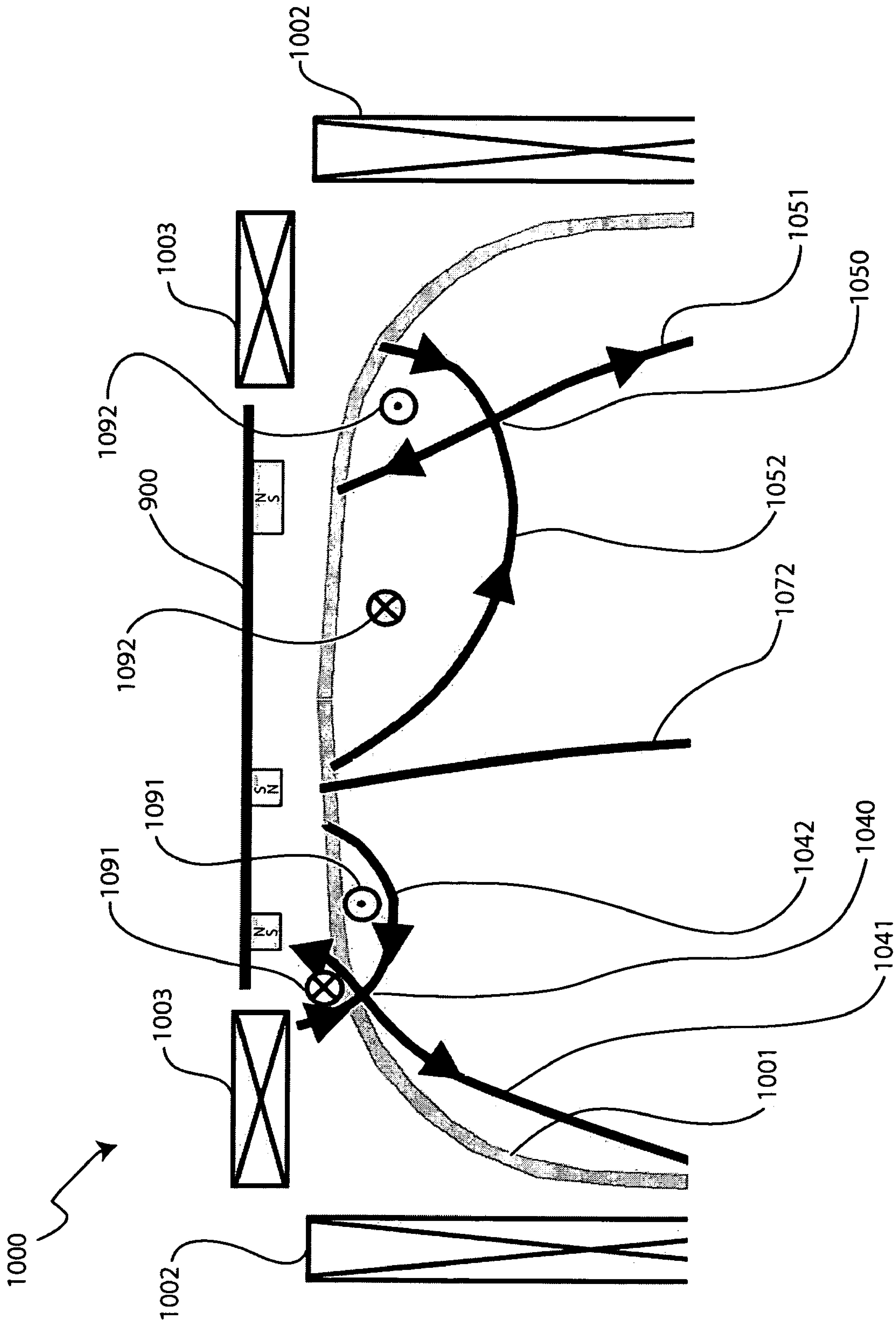

1002
1003
1092
900
1092
1091
1091
1003
1000
1002
1051
1050
1052
1072
1042
1040
1041
1001
N
S

FIG. 10B

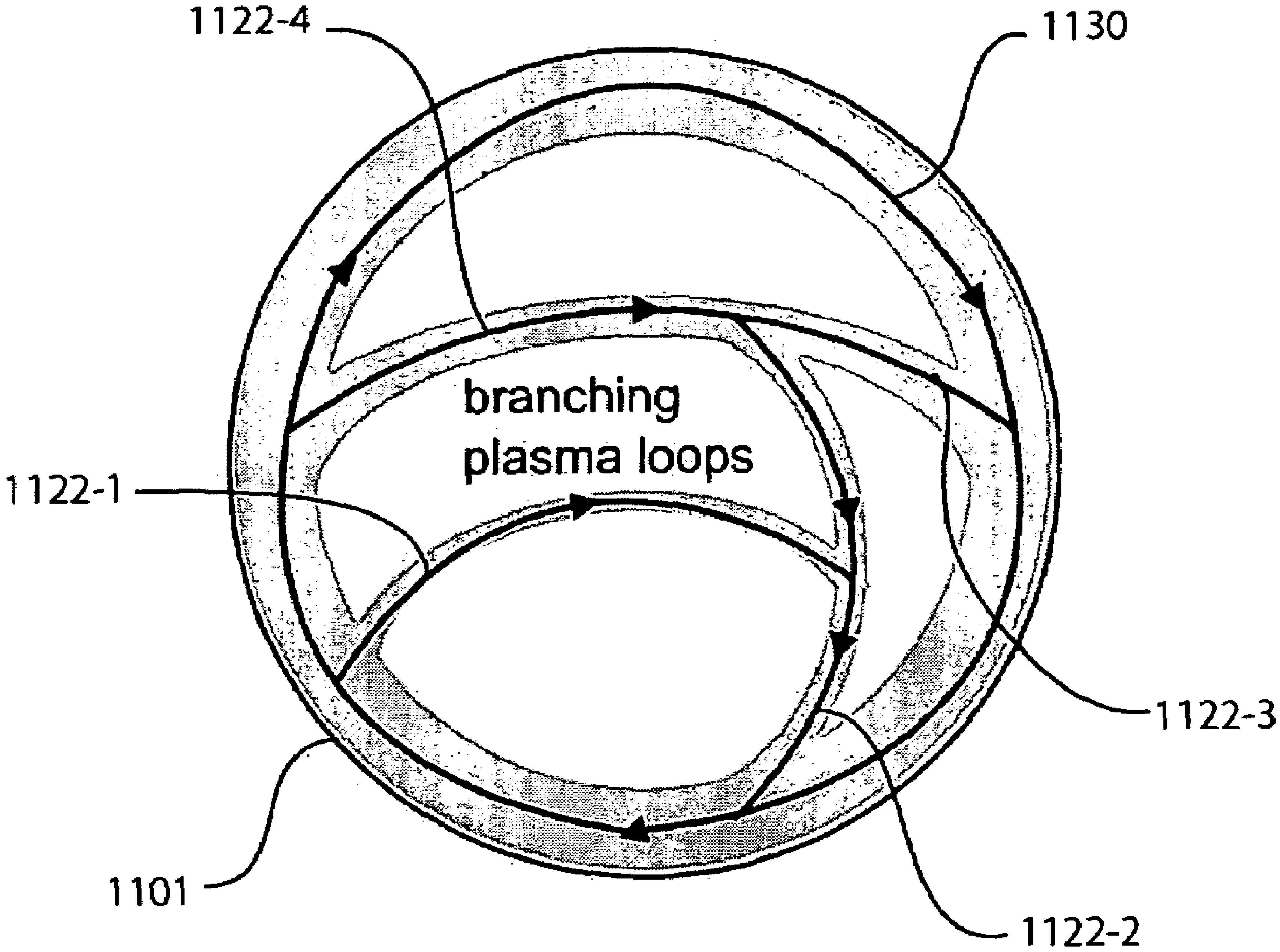

1122-4
1130
branching
plasma loops
1122-1
1122-3
1101
1122-2

FIG. 11

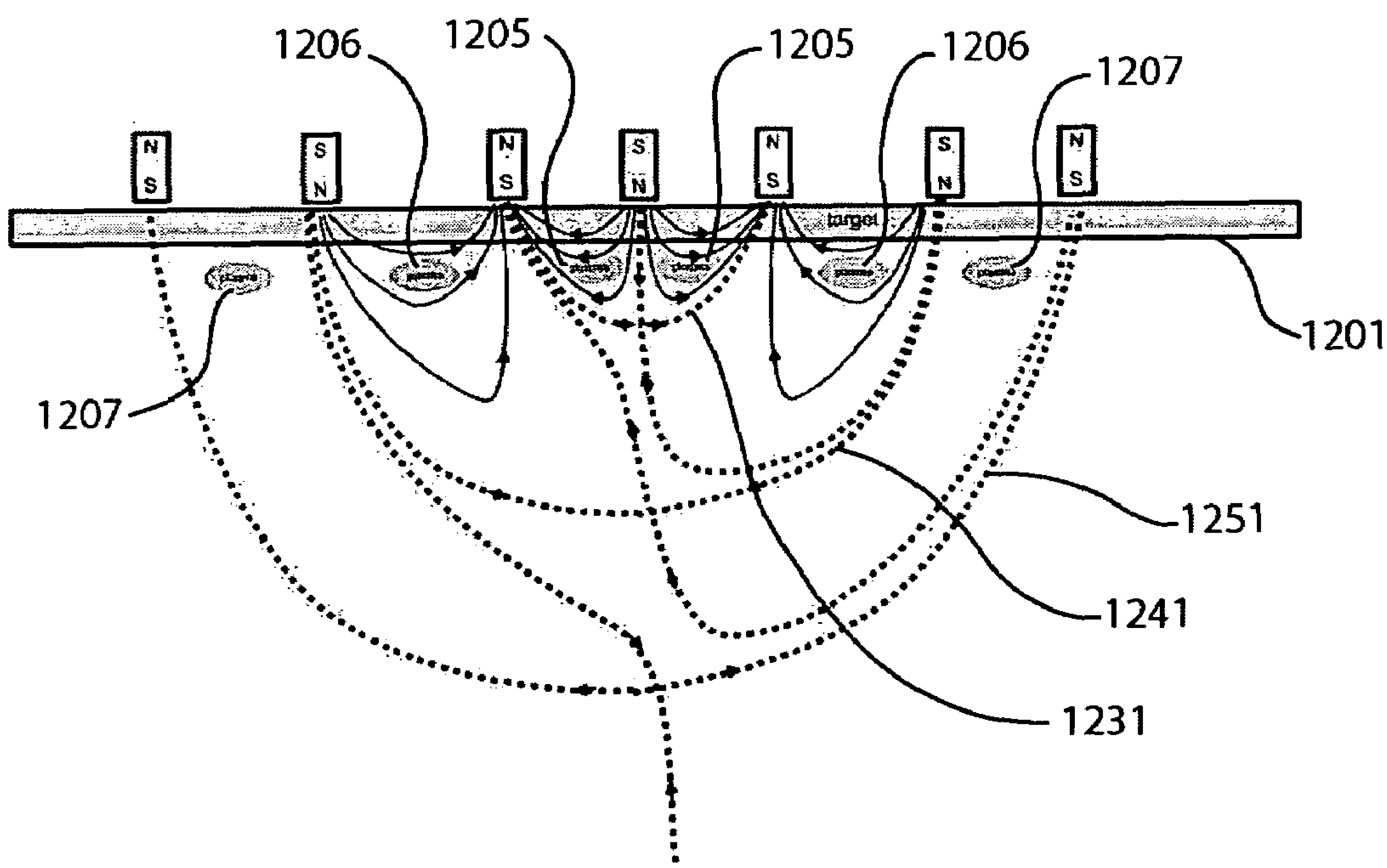

1206
1205
1205
1206
1207
N
S
target
1201
1207
1251
1241
1231

FIG. 12

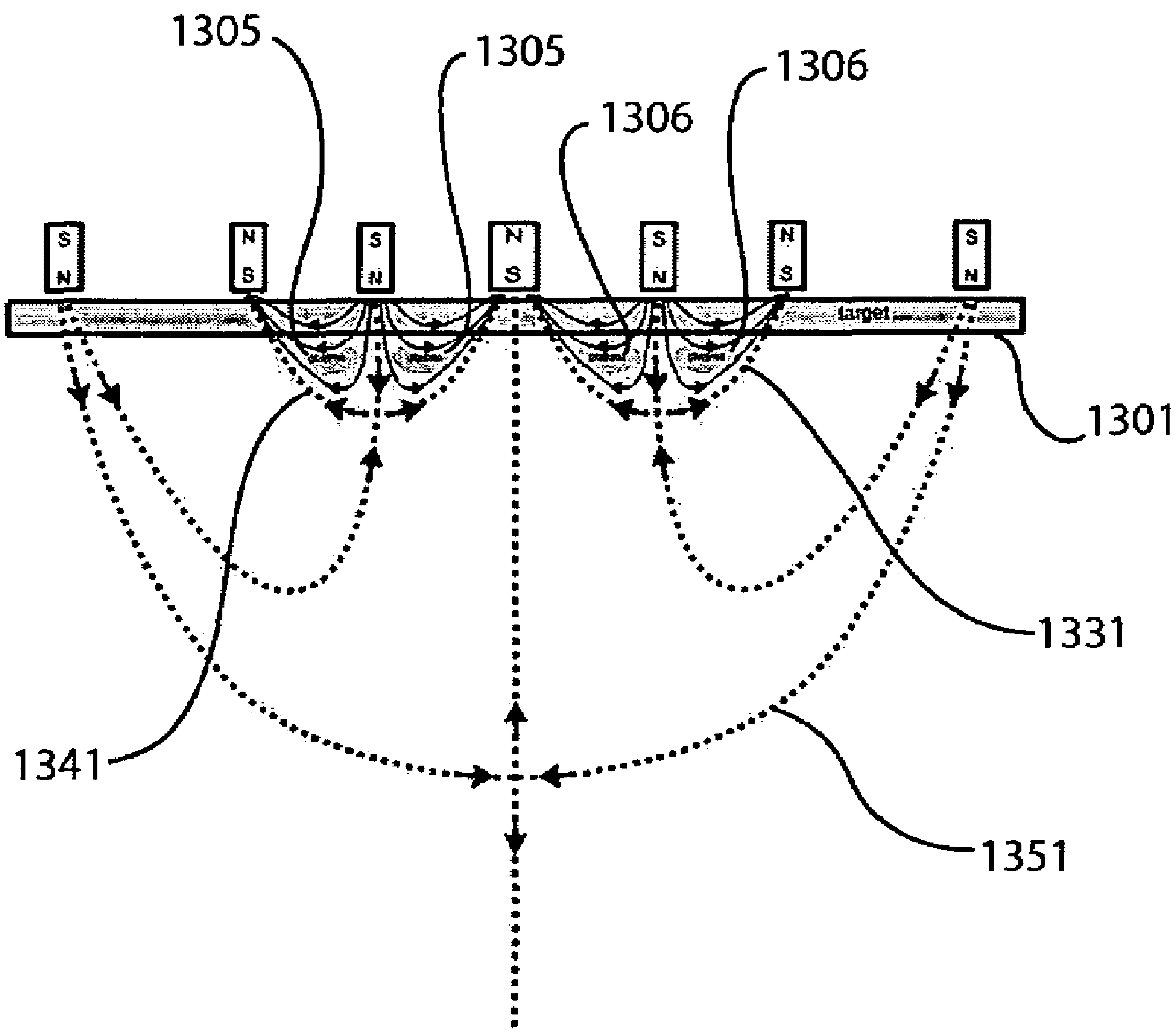

1305
1305
1306
1306
S
N
N
S
S
N
N
S
S
N
N
S
S
N
target
1301
1331
1341
1351

FIG. 13

METHODS AND APPARATUS FOR MAGNETRON SPUTTERING

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to integrated circuit fabrication equipment, and more particularly but not exclusively to magnetron sputtering.

2. Description of the Background Art

Magnetron sputtering, in general, is well known in the art of integrated circuit fabrication. A magnetron sputtering apparatus includes a target comprising a material to be deposited on a substrate. The substrate, which may be a semiconductor wafer, is located a distance away from the target. To coat the substrate with the target material, a plasma of a gas suitable for sputtering is maintained between the target and the substrate. When ions of the sputtering gas hit the target, atoms of the target material are dislodged from the target and onto the substrate.

FIG. **1**A schematically shows an example magnetron sputtering apparatus **100**. Apparatus **100** includes a target **101** and a magnetic circuit comprising magnets **121**, **122**, and **123**. Magnets **121**, **122**, and **123** and their respective magnetic fields **104** (i.e., **104-1**, **104-2**, . . .) are cylindrically symmetric about a center line **112**. A plasma loop **105** is maintained to sputter a target **101**, which is a planar target in this example. A "plasma loop" comprises plasma formed in a region or path. In apparatus **100**, magnets **121**, **122**, and **123** are configured such that magnetic fields **104** confine plasma loop **105**. The effectiveness of the confinement depends on the strength of magnetic fields **104**. However, in apparatus **100**, electrons in plasma loop **105** have a tendency to diffuse to regions of weak magnetic fields and escape to the chamber walls. This makes it relatively difficult to maintain a high density plasma in front of target **101**.

The sputtering track on a target generally follows the shape of the plasma loop formed over the target. For example, because ions from plasma loop **105** sputter target **101**, target **101** is eroded only in areas under plasma loop **105**. FIG. **1**B is a plan view schematically showing a ring-shaped sputtering track formed by plasma loop **105** on target **101**.

SUMMARY

In one embodiment, a magnetron sputtering apparatus forms a closed plasma loop and an open plasma loop within the closed plasma loop. The open plasma loop allows for relatively uniform erosion on the face of a target by broadening the sputtered area of the target. The open plasma loop may be formed and rotated using a rotating magnetic array to distribute the target erosion.

These and other features of the present invention will be readily apparent to persons of ordinary skill in the art upon reading the entirety of this disclosure, which includes the accompanying drawings and claims.

DESCRIPTION OF THE DRAWINGS

FIG. **1**A schematically shows an example magnetron sputtering apparatus.

FIG. **1**B is a plan view schematically showing a plasma loop formed by the apparatus of FIG. **1**A.

FIG. **2**A schematically shows an example magnetron sputtering apparatus comprising one separatrix surface within another.

FIG. **2**B is a plan view schematically showing the two plasma loops formed by the apparatus of FIG. **2**A.

FIGS. **3**–**6** are plan views schematically showing various combinations of open and closed plasma loops in accordance with embodiments of the present invention.

FIG. **7**A schematically shows a magnetron sputtering apparatus employing perpendicularly oriented magnets to form an open plasma loop.

FIG. **7**B is a plan view schematically showing the locations of a plasma loop and magnets relative to the target of the apparatus of FIG. **7**A.

FIG. **8**A schematically shows a magnetron sputtering apparatus employing magnets that are oriented parallel to a target to form an open plasma loop.

FIG. **8**B is a plan view schematically showing the use of the apparatus of FIG. **8**A to form an open plasma loop.

FIGS. **9**A and **9**B are plan views schematically showing rotating magnetic arrays in accordance with embodiments of the present invention.

FIG. **10**A schematically shows a magnetron sputtering apparatus in accordance with an embodiment of the present invention.

FIG. **10**B shows a magnified view of the apparatus of FIG. **10**A.

FIG. **11** is a plan view schematically showing branching plasma loops in accordance with an embodiment of the present invention.

FIGS. **12** and **13** schematically show magnetron sputtering apparatus in accordance with embodiments of the present invention.

The use of the same reference label in different drawings indicates the same or like components. Drawings are not necessarily to scale unless otherwise noted.

DETAILED DESCRIPTION

In the present disclosure, numerous specific details are provided such as examples of apparatus, components, and methods to provide a thorough understanding of embodiments of the invention. Persons of ordinary skill in the art will recognize, however, that the invention can be practiced without one or more of the specific details or by using alternatives. For example, magnets shown as permanent magnets may be replaced by electromagnets and vice versa. In other instances, well known details are not shown or described to avoid obscuring aspects of the invention.

FIG. **2**A schematically shows an example magnetron sputtering apparatus **200** comprising one separatrix surface within another. Apparatus **200** includes a planar target **201** and a magnetic circuit comprising magnets **241**–**245** (i.e., **241**, **242**, **243**, **244**, and **245**). Magnets **241**–**245** and their magnetic fields are substantially cylindrically symmetric. The magnetic circuit of apparatus **200** is configured to generate a separatrix **212** and a separatrix **223**. Generally speaking, a separatrix is a two-dimensional surface in three dimensions that divides a magnetic field into two regions. On either side of a separatrix, neighboring magnetic field lines remain roughly parallel to each other. But magnetic field lines that are on different sides of the separatrix will diverge, even if they are arbitrarily close at some point in space. A common (but not defining) feature of a separatrix surface is a region of low magnetic field, called the "null field" region. Plasma that is otherwise confined by the separatrix can escape out of the separatrix through a null region. In apparatus **200**, electrons may escape through null regions **213** and **222** The formation and use of a separatrix in a magnetron sputtering apparatus are also disclosed in the following disclosures, which are incorporated herein by reference in their entirety: U.S. Pat. No. 5,482,611, U.S. Pat. No. 6,179,973, U.S. Pat. No. 6,444,105, U.S. Pat. No. 6,471,831, U.S. Pat. No. 6,497,796, U.S. Pat. No. 6,613,199, and U.S. application Ser. No. 10/068,772, entitled "Null-Field Magnetron Apparatus With Essentially Flat Target," filed by Kwok F. Lai on Feb. 5, 2002.

Apparatus **200** has several advantages. First, it has two separate plasma loops that can be optimized somewhat independently. Second, electrons of plasma loop **205** escaping out of separatrix **212** are recaptured by separatrix **223**, effectively recycling the plasma and increasing the efficiency of apparatus **200**.

FIG. **2**B schematically shows the sputtering tracks formed by plasma loops **205** and **206** on target **201**. Plasma loops **205** and **206** are closed plasma loops in that the plasma flows along closed loop paths. The area of the target adjacent to the gap between plasma loops **205** and **206** on target **201** does not get eroded as much as the areas adjacent to the plasma loops. In some situations, this is the case even if plasma loop **205** is of various closed loop shapes (e.g., heart, slice of pie, kidney, etc.) and rotated. The formation and use of rotating magnetic fields in a magnetron sputtering apparatus are also disclosed in U.S. Pat. No. 5,314,597 and U.S. Pat. No. 6,193,854, which are incorporated herein by reference in their entirety.

FIGS. **3**–**6** are plan views schematically illustrating various combinations of open and closed plasma loops (and hence sputtering tracks) in accordance with embodiments of the present invention. The plasma loops of FIGS. **3**–**6** may be formed using any suitable magnetic circuit without detracting from the merits of the present invention. For example, a rotating magnetic array may be employed to form and rotate the plasmas to achieve relatively uniform erosion on the face of their respective targets. The targets may be hollow, planar, or of other shapes depending on the application. As can be appreciated, a hollow target may be a cup or cylindrically shaped target. Hollow target magnetrons are also disclosed in the incorporated disclosures U.S. Pat. No. 5,482,611, U.S. Pat. No. 6,179,973 and U.S. Pat. No. 6,613,199. In FIGS. **3**–**6**, and in other figures of the present disclosure, the direction of plasma flow is indicated by arrows, and is primarily due to ExB (cross product of electric and magnetic fields) drift.

For purposes of the present disclosure, an "open plasma loop" refers to a plasma loop that takes plasma from a first region, siphons that plasma through the open loop, and then releases that plasma into a second region. The first and second regions, which are not part of the open plasma loop, may be the same region. As will be more apparent below, the just mentioned first and second regions may be a nearby volume, a closed plasma loop, or another open plasma loop.

In FIG. **3**, a plasma loop **325** is formed within the separatrix confining plasma loop **305** over a target **301**. Plasma loop **325** is an open plasma loop in that it takes plasma from a surrounding volume, siphons that plasma through plasma loop **325** in the direction indicated by an arrow **322**, and then releases that plasma back to the surrounding volume. Plasma loop **305** is a closed plasma loop that flows in the direction indicated by an arrow **302**.

An open plasma loop can also be attached to a closed plasma loop to siphon plasma from the closed plasma loop on an alternate path across the target and back into the closed plasma loop. This is illustrated in FIG. **4**, where open plasma loop **425** branches off closed plasma loop **405** across target **401** and back into closed plasma loop **405**. Plasma loops **405** and **425** flow in the directions indicated by arrows **402** and **422**, respectively.

In light of the present disclosure, those of ordinary skill in the art will appreciate that the above-described open plasma loops may be adapted to suit specific applications. For example, the teachings of the plasma topologies of FIGS. **3** and **4** may be combined to form an open plasma loop that siphons plasma from a closed plasma loop and releases the siphoned plasma into a nearby general volume, or siphons plasma from a general nearby volume and into a closed plasma loop.

An open plasma loop may be employed in parallel with a closed plasma loop to broaden the area of the closed plasma loop. This is illustrated in FIG. **5** where plasma loop **525** is formed in parallel with and adjacent to a plasma loop **505** over a target **501**. Open plasma loop **525** and closed plasma loop **505** flow in the direction indicated by arrows **522** and **502**, respectively.

An open plasma loop may be employed in conjunction with one or more closed plasma loops. In FIG. **6**, open plasma loop **625** contains plasma that flows in the direction indicated by an arrow **622**, closed plasma loop **605** contains plasma that flows in the direction indicated by an arrow **602**, and closed plasma loop **635** contains plasma that flows in the direction indicated by an arrow **632**. Plasma loops **625** and **635** may be formed and rotated by a rotating magnetic array to average the erosion over the entire face of target **601**.

An open plasma loop may be formed using a magnetic circuit having individual magnets that are oriented perpendicular to the surface of the target. For example, as shown in FIG. **7**A, magnets **708** and **709** may be configured such that a plasma loop **705** is an open plasma loop. However, depending on nearby magnetic circuits, auxiliary sputtering tracks may form in the field loops generally bounded by dashed lines **781** and **782** and provide a return path for plasma loop **705** (the main sputtering track). This may result in plasma loop **705** becoming a closed plasma loop instead of an open plasma loop. FIG. **7**B is a plan view schematically showing the locations of plasma loop **705** and magnets **708** and **709** relative to target **701**. Although magnets **708** and **709** provide parallel rows of opposite magnetic poles, a nearby prevailing magnetic "N" field (not shown) may couple with the "S" field of magnet **709** to form a closed plasma loop around magnet **709** as shown in FIG. **7**B. Of course, this depends on whether there will be interfering magnetic field lines. Using perpendicularly oriented magnets, such as magnets **708** and **709**, to form an open plasma loop may be feasible in some magnetic configurations (e.g., see rotating magnetic array **900** of FIGS. **9**A and **9**B).

A relatively easier way of forming an open plasma loop is to employ magnets that are oriented parallel to the target surface. This embodiment of the present invention is schematically illustrated in FIG. **8**A. In FIG. **8**A, a magnet **808** is oriented parallel to a target **801**. Because there are no field loops on either side of plasma loop **805**, the chances of having an unintended auxiliary track is decreased. Several magnets **808** (i.e., **808-1**, **808-2**, . . .) may be placed side by side to form a continuous open loop path as shown in the plan view of FIG. **8**B. FIG. **8**B shows the locations of magnets **808** and plasma loop **805** relative to target **801**. In FIG. **8**B, plasma loop **805** flows across target **801** in the direction indicated by an arrow **809**. Magnets **808** may be configured to achieve a particular type of open plasma loop. In the interest of clarity, FIG. **8**A does not show all of the magnetic components. For example, in order to form a self-sustaining magnetron plasma, it may be necessary to employ additional magnets to enclose plasma **809** within a separatrix surface containing a closed plasma loop.

FIG. **9**A is a plan view schematically showing a rotating magnetic array **900** in accordance with an embodiment of the present invention. Array **900** includes magnetic circuits **903** and **930**, which both comprise magnets oriented perpendicularly to the face of the target (not shown). FIG. **9**A shows the poles of the magnets of magnetic circuits **903** and **930** as "seen" by the target. Magnetic circuit **903** is configured to form an open plasma loop similar to plasma loop **625** shown in FIG. **6**, while magnetic circuit **930** is configured to form an inner closed plasma loop similar to plasma **635** also shown in FIG. **6**. Magnets **932** and **933** of magnetic circuit **930** interact with a prevailing "N" field (e.g., those from magnets **1002** and **1003** shown in FIG. **10**A) and magnetic fields generated by magnets **931** (i.e., **931-1**, **931-2**, . . .) to form an inner closed plasma loop. FIG. **9**B is a plan view schematically showing a rotating magnetic array **960** in accordance with an embodiment of the present invention. Magnetic array **960** is similar in operation to magnetic array **900**. Both magnetic arrays **900** and **960** employ a magnetic circuit **903**, configured to form an open plasma loop similar to plasma loop **625** shown in FIG. **6**. In the embodiment shown in FIG. **9**A, magnets **932** and **933** interact with magnets **931** (i.e., **931-1**, **931-2**, . . .) and a locally prevailing N magnetic field to form a closed plasma loop similar to loop **635** shown in FIG. **6**. In the embodiment shown in FIG. **9**B, magnet **962** serves the same purpose as magnets **932** and **933** in FIG. **9**A, interacting with the prevailing N field to form a closed plasma loop similar to loop **635** shown in FIG. **6**. In the embodiment shown in FIG. **9**B, there are no magnets analogous to magnets **931** in FIG. **9**A. These magnets are not required to form a closed plasma loop, but can be useful for fine tuning the erosion of the target.

FIG. **10**A shows a magnetron sputtering apparatus **1000** in accordance with an embodiment of the present invention. Apparatus **1000** includes magnetic array **900** (see FIG. **9**A). Magnetic array **900** may be rotated using a motor, for example, to average the erosion profile on a hollow target **1001**. In apparatus **1000**, target **1001**, an auxiliary magnet **1003**, a main magnet **1002**, and a control magnet **1004** are cylindrically symmetric. The teachings of the present disclosure may be employed together with the teachings of the incorporated U.S. Pat. Nos. 6,497,796, 6,179,973, and 6,193,854 to build apparatus **1000**. It should be understood, however, that the present invention is not so limited and may be generally employed in other magnetron sputtering apparatus.

In apparatus **1000**, magnets **1002** and **1004** generate magnetic fields to form a separatrix **1071** that confine an outer closed plasma loop (e.g., see plasma loop **605** shown in FIG. **6**). Plasma confined by separatrix **1071** escapes out of target **1001** through a null region **1070** generally along the path of a magnetic field line **1072**. Some of the escaping ions get deposited on a substrate **1060**, which may be a semiconductor wafer. The magnetic field strength of control magnet **1004**, which may be an electromagnet, may be varied to control the shape of separatrix **1071** and thereby affect the profile of the escaping plasma.

Auxiliary magnet **1003** and the magnetic circuits of magnetic array **900** are configured to form a separatrix **1042** and a separatrix **1052**. Separatrix **1042** and separatrix **1052** pass through null regions **1040** and **1050**, respectively. Plasma may escape out of separatrix **1042** by following the path of a magnetic field line **1041**. Similarly, plasma may escape out of separatrix **1052** by following the path of a magnetic field line **1051**.

FIG. **10**B shows a magnified view of the top portion of apparatus **1000**. As shown in FIG. **10**B, separatrix **1042** is formed such that it is cut off by the face of target **1001**. This results in a plasma loop **1091** that would otherwise flow going into the page of FIG. **10**B (see the circled X labeled **1091**) and coming out of the page of FIG. **10**B (see the circled dot labeled **1091**) to be also cut off. Plasma loop **1091** does not have a return path and thus becomes an open plasma loop flowing in only one direction across target **1001** (see plasma loop **625** of FIG. **6**). On the other hand, separatrix **1052** is not cut off. This allows plasma loop **1092** confined by separatrix **1052** to flow in a direction going into the page of FIG. **10**B (see circled X labeled **1092**) and coming out of the page of FIG. **10**B (see circled dot labeled **1092**). Plasma loop **1092** has an unblocked return path and is thus a closed plasma loop (see plasma **635** of FIG. **6**). The other labeled features in FIG. **10**B have already been introduced and discussed in connection with FIG. **10**A.

While specific embodiments of the present invention have been provided, it is to be understood that these embodiments are for illustration purposes and not limiting. Many additional embodiments will be apparent to persons of ordinary skill in the art reading this disclosure. For example, referring to FIG. **11**, the teachings of the present disclosure may be employed to form multiple branching open plasma loops flowing in the directions indicated by arrows **1122** (i.e., **1122-1**, **1122-2**, . . .) over a target **1101**. In FIG. **11**, a closed plasma loop flows in the direction indicated by an arrow **1130**. Furthermore, the recycling of plasma from one confinement region into another confinement region may be extended to any number of confinement regions. For example, FIG. **12** schematically shows a separatrix **1231** confining a plasma loop **1205**, which is within a separatrix **1241** confining a plasma loop **1206**, which in turn is within a separatrix **1251** confining a plasma loop **1207** over a target **1201**. In FIG. **12**, plasma escaping from separatrix **1231** may be captured and recycled by separatrix **1241**. Similarly, plasma escaping from separatrix **1241** may be captured and recycled by separatrix **1251**. It is also not necessary for each layer of separatrix to be concentric. For example, FIG. **13** shows a separatrix **1341** confining a plasma loop **1305**, and a separatrix **1331** confining a plasma loop **1306**. As shown in FIG. **13**, separatrices **1331** and **1341** are not concentric and are both within a separatrix **1351**. The present invention is thus limited only by the following claims.

What is claimed is:

1. A method of magnetron sputtering, the method comprising:
- forming a first closed plasma loop;
- forming an open plasma loop by forming a separatrix such that a portion of the open plasma loop enclosed by the separatrix is cut-off by a target of a magnetron apparatus, the separatrix comprising a surface having a null region through which ions may pass through; and
- sputtering the target with ions from the open plasma loop and the closed plasma loop.

2. The method of claim **1** further comprising:
- forming a second closed plasma loop within the first closed plasma loop.

3. The method of claim **1** wherein the open plasma loop flows in the same direction as the first closed plasma loop.

4. The method of claim **1** wherein the target comprises a planar target.

5. The method of claim **1** wherein the target comprises a hollow target.

6. The method of claim 1 further comprising:
generating a rotating magnetic field to rotate the open plasma loop.

7. A method of magnetron sputtering, the method comprising:
forming a first closed plasma loop;
forming an open plasma loop;
sputtering a target with ions from the open plasma loop and the closed plasma loop;
wherein the open plasma loop is formed by physically blocking a return path of a separatrix comprising a surface having a null field region through which ions may pass through.

8. The method of claim 7 further comprising:
forming a second closed plasma loop within the first closed plasma loop.

9. The method of claim 7 wherein the open plasma loop flows in the same direction as the first closed plasma loop.

10. The method of claim 7 wherein the target comprises a planar target.

11. The method of claim 7 wherein the target comprises a hollow target.

12. The method of claim 7 further comprising:
generating a rotating magnetic field to rotate the open plasma loop.

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